the Energy to Lead

Oxy-Combustion Pressurized Fluidized Bed with Carbon Dioxide Purification

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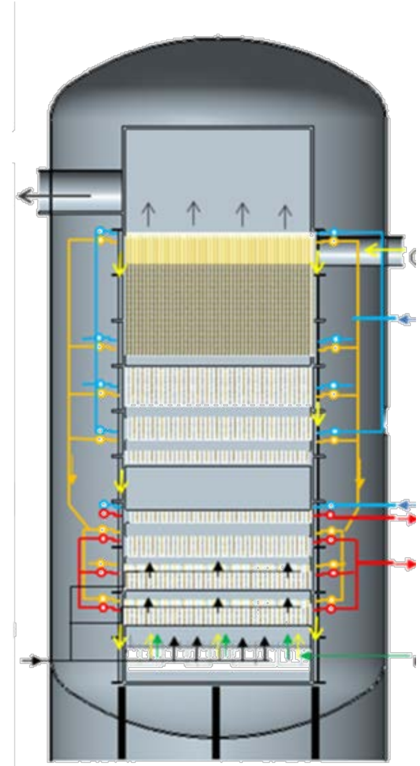
Agenda

- Project Overview
- Background
- Technical Approach / Project Scope
- Progress and Current Status
- Future Plans
- Summary



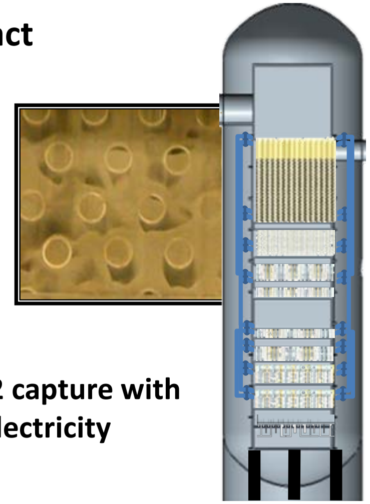
Commercial scale Oxy-PFBC

Phase II Oxy-fired Pressurized Fluidized Bed Combustor (Oxy-PFBC) Overview

Description and Impact

Phase II Description

- Advance Oxy-PFBC technology to TRL 6 through pilot testing
- Budget: $19.1M ($12M DOE funding)
- Period of Performance: 39 months (7/1/2014 - 9/30/2017)
- Impact: Exceed DOE Goals of >90% CO2 capture with no more than 35% increase in cost of electricity



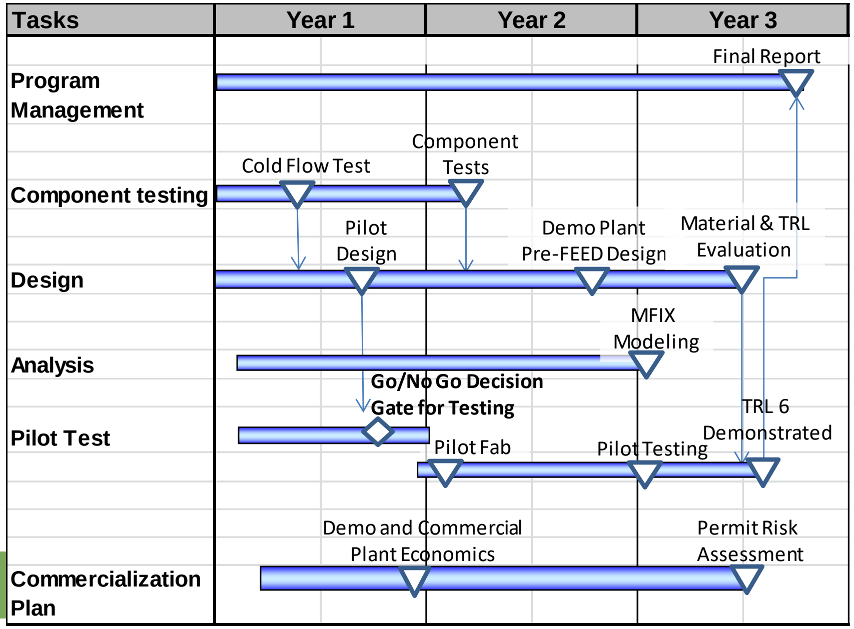
Team Members and Roles

- **Gas Technology Institute (GTI)** – Lead, PFBC technology
- **Linde, LLC** – Gas supply, CPU technology, HEX design
- **CanmetENERGY** – Pilot plant test facility and test support
- **GE**– PFBC design support and commercialization partner
- **Pennsylvania State University (PSU)** – Fuel & limestone testing, agglomeration model development
- **Electric Power Research Institute (EPRI)** – End user insight, review of process and cost modeling

Project Objectives

- Assess the components of the system designed in Phase I to confirm scalability, performance, and cost
- Test the system at subscale pilot facility to evaluate system performance and operability
- Develop algorithms to model the components and system for scale-up
- Use the validated models to predict commercial scale cost of electricity
- Develop Phase III project plan, risk mitigation status and TRL advancement, and identify partners and sites for 30-50 MWth plant

Schedule



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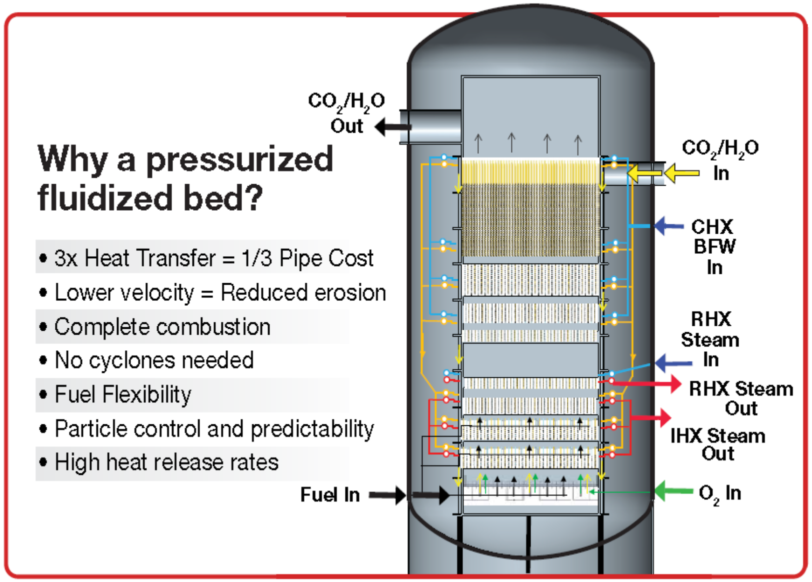
Oxy-PFBC Technology Overview

INNOVATION

- High power density reactor for coal-fired plants with CO2 capture
  - In-bed heat exchanger for ultra-compact combustor
  - Elutriated flow removes ash and sulfur prior to CO2 recycle
  - 1/3 the size and half the cost of traditional boiler

BENEFITS

- Produces affordable electric power with near zero emissions
- Produces steam for heavy oil recovery using low value feedstock (petcoke, coal, biomass)
- Produces pure CO_2 for Enhanced Oil Recovery (EOR)



Commercial Scale PFBC Concept

MARKETS

- Electric power generation with CO_2 capture, including CHP
- Heavy oil production (once-through steam)
- Light oil production (CO_2 floods)

STATUS

- Long-life, in-bed heat exchangers demonstrated in 1980s
- Two active DOE contracts
- Next step: TRL 6 by Spring 2017 with Pilot scale (1 MWth) testing

Heritage Rocketdyne Test Facility that Demonstrated Long Life In-bed Heat Exchanger

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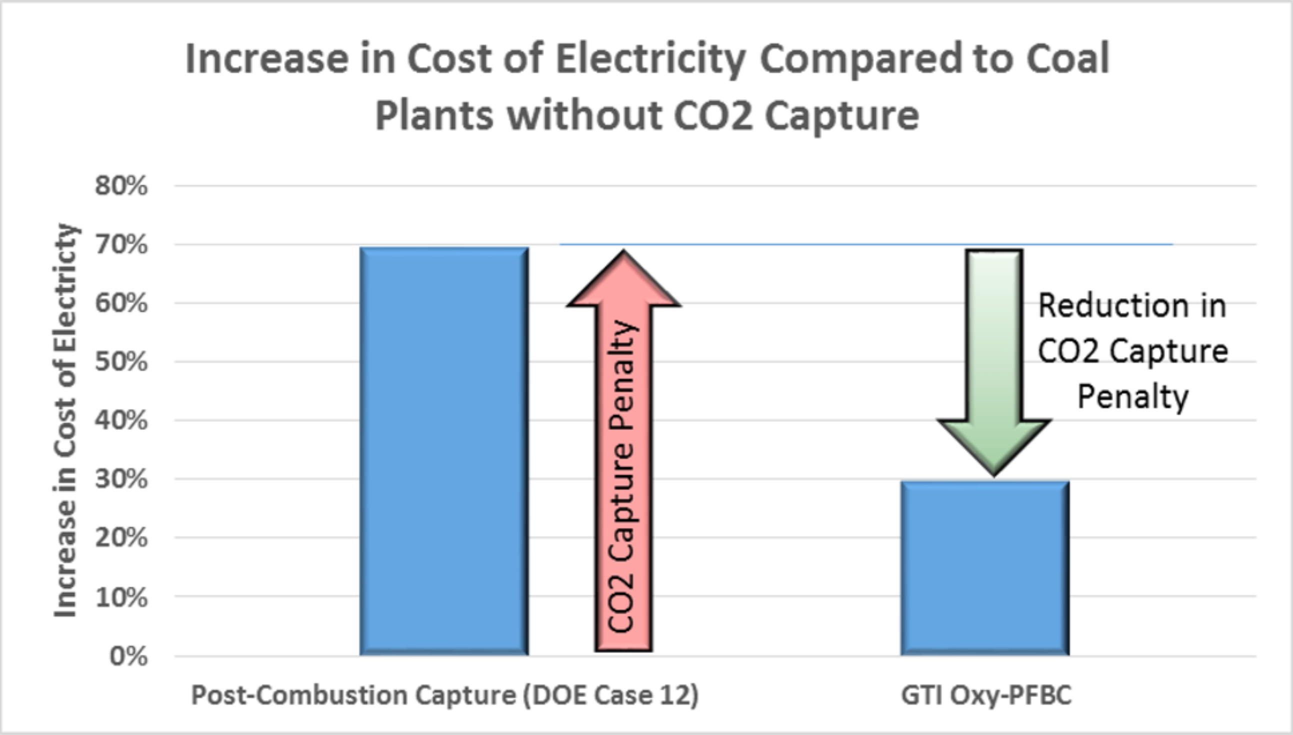
Technoeconomic Analysis Results



- TEA updated to reflect component testing results
  - Component testing validated design assumptions – no change to performance
- Primary contributors to reduced cost include significantly reduced CapEx from lower cost combustor and gas cleanup equipment

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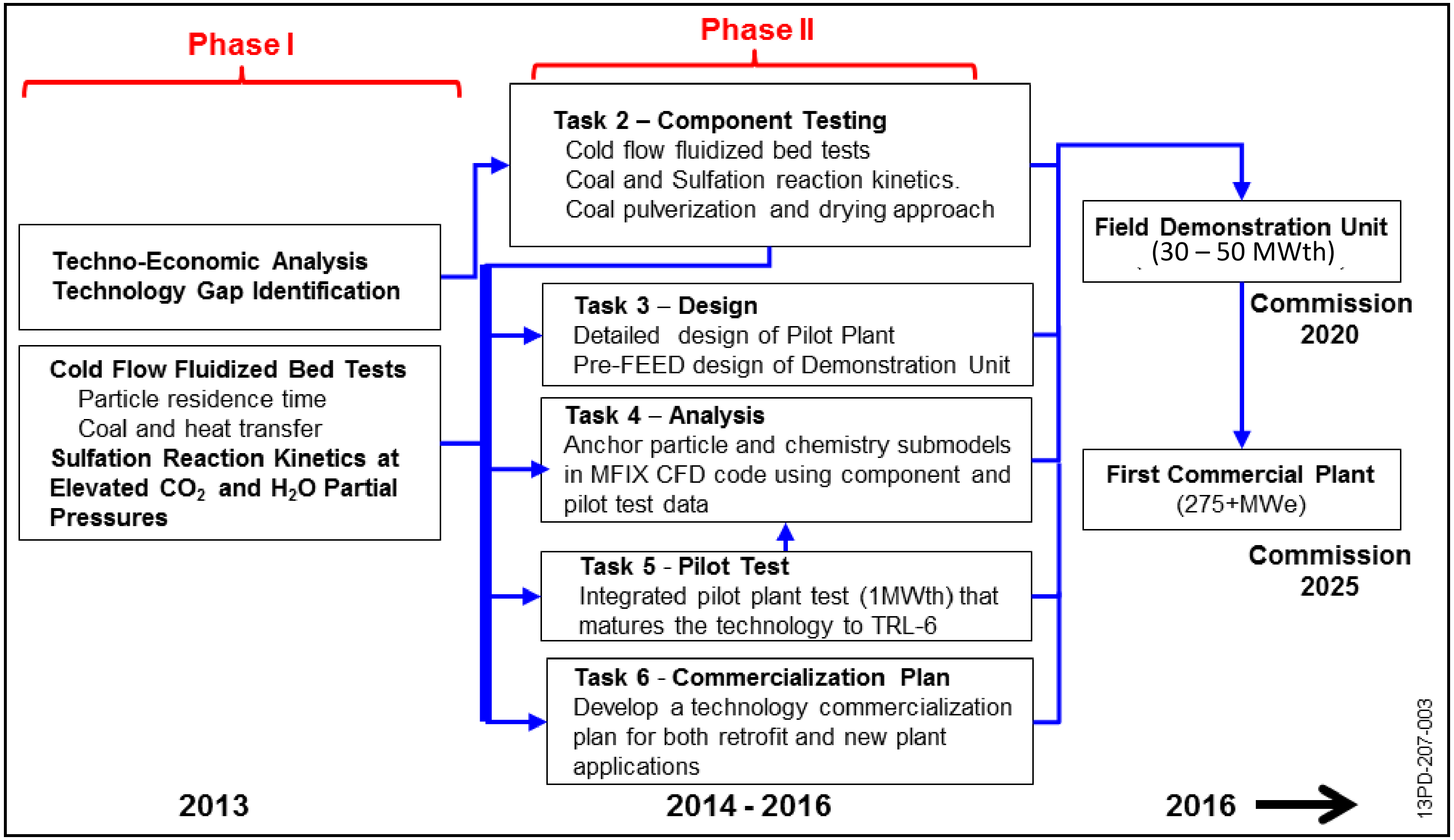
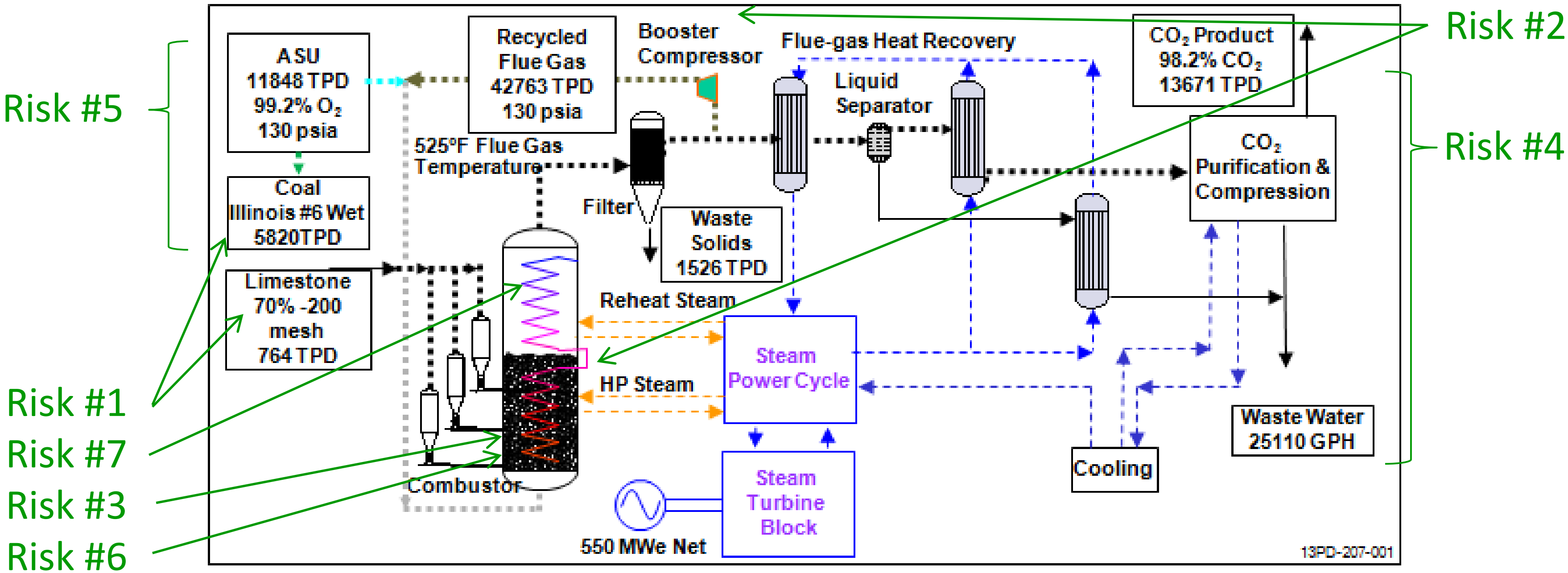
Technical Approach



- **Success Criteria:** Provide knowledge for target operating conditions and design features for the demonstration and commercial scale units. Examples:
  - Use test data to calibrate models for combustion, bed stability and heat removal, enabling a trade of bed height and staging strategy for commercial plants
  - Pressurized staged oxy-combustion system operation is characterized to develop operability criteria and scaled-up system requirements

Risks for Commercial System Development



Risks/mitigation

1) Reaction chemistry is too fast/slow
Mitigation: *Coal and sulfation reaction testing, Pilot plant testing*

2) Bubbling bed fluidizing velocity inappropriate or unstable
Mitigation: *Cold flow fluidized bed testing, Pilot plant testing*

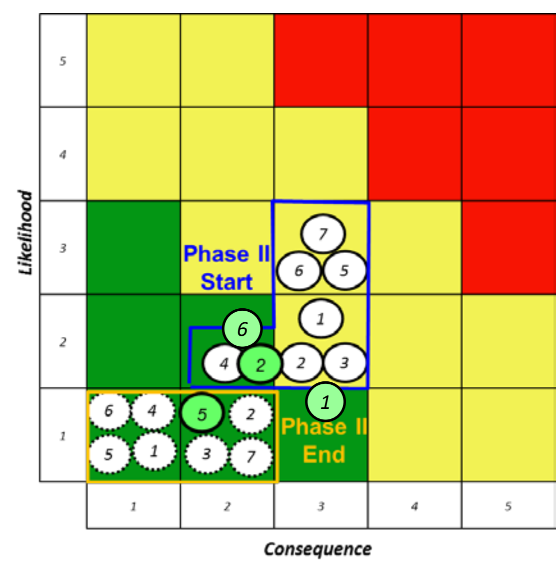
3) In-bed HEX erosion/corrosion shortens life
Mitigation: *Cold flow fluidized bed testing, Pilot plant testing*

4) Flue Gas does not meet emissions or pipeline specs
Mitigation: *Pilot plant testing*

5) Pulverization and drying of coal lowers efficiency by using too much CO2 or heat
Mitigation: *Use waste heat for drying*

6) Inert particles change size over time leading to inoperable conditions
Mitigation: *Pilot plant testing and analysis*

7) Corrosion in convective HEX or recycle gas due to exceeding acid dewpoint limits
Mitigation: *Pilot plant testing and analysis*



Commissioning Approach

- Commissioning Phase 1: Leak and Gas Distribution Flow Tests
  - **Objectives**: Cold flow of fluids through all gas and fluid systems. Testing of flow and pressure loops including startup / shutdown sequences and power loss scenario.
  - **Status**: **Complete**
- Commissioning Phase 2: Solids Flow Systems
  - Objectives: Cold flow operation of all solid material systems, including filters and solids removal. Bed behavior characterized at elevated pressure.
  - **Status**: **Complete**
- Commissioning Phase 3: Warm-up Systems
  - Objectives: Characterize operation of startup burner/heater and heat tracing. Test startup/shutdown procedures, bed behavior at elevated temp and pressure.
  - **Status**: **Complete**
- Commissioning Phase 4: Coal Start-up and Shut-Down
  - Objectives: Characterize operation of system with coal ignition and burning. Test startup/shutdown procedures, gas cleanup equipment at elevated temp and pressure.
  - **Status**: **Complete**

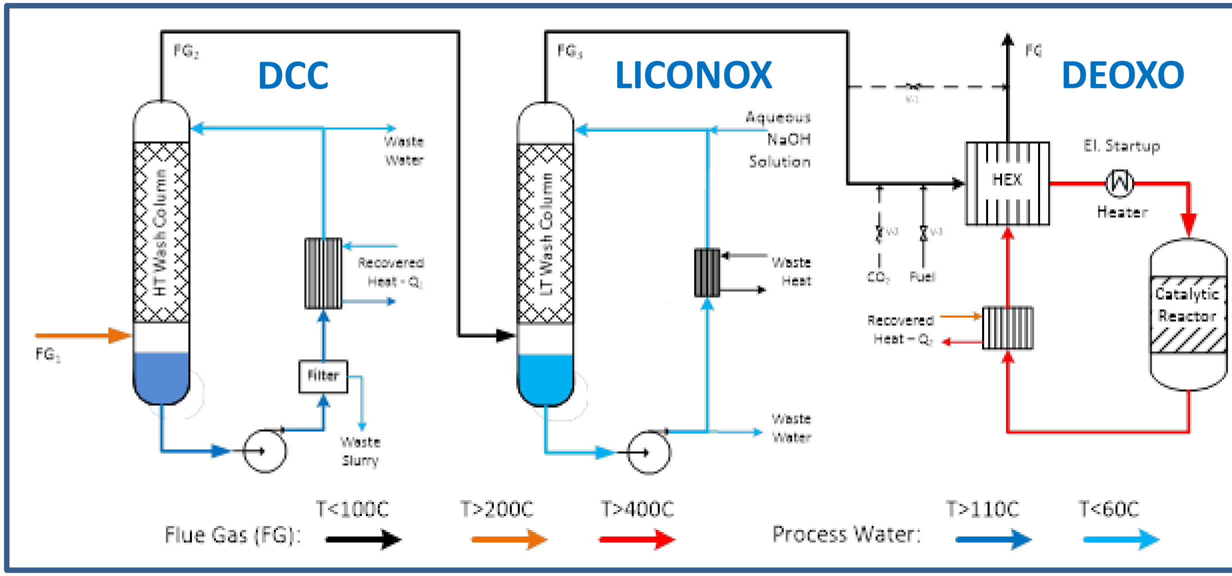
Performance checks of safety equipment and procedures conducted during each phase

Performance Test Objectives

- Validate assumptions for sulfur capture and flue gas purification
- Explore the effect of oxygen mole % on carbon burnout and particle agglomeration.
- Explore the effect of bed depth on carbon burnout
- Validate particle reaction rates and residence time requirements
- Validate thermal models for system level heat integration
- Validate operational procedures
  - Natural gas warm up to coal ignition temperatures
  - Transition to oxy-Combustion at pressure
  - Control recycle gas flow rates and temperatures
  - Control bed depth
  - Solids injection and removal systems

CO_2 Purification Unit (CPU) Test Approach

- **CPU includes 3 components**
  - **Direct Contact Cooler (DCC)** – Cools flue gas, condenses water, recovers heat, removes ash and HCl
  - **LICONOX** – Removes NOx and residual SOx
  - **DEOXO** – Removes O_2 and recovers heat



- **Commissioning includes 2 phases**
  - **Operational tests** – Demonstrates that all pipes, valves and instrumentation are properly installed, and all control and safety systems operate as designed
  - **Efficiency tests** – Demonstrate efficiencies of temperature and condensate flowrate control systems for DCC and LICONOX columns

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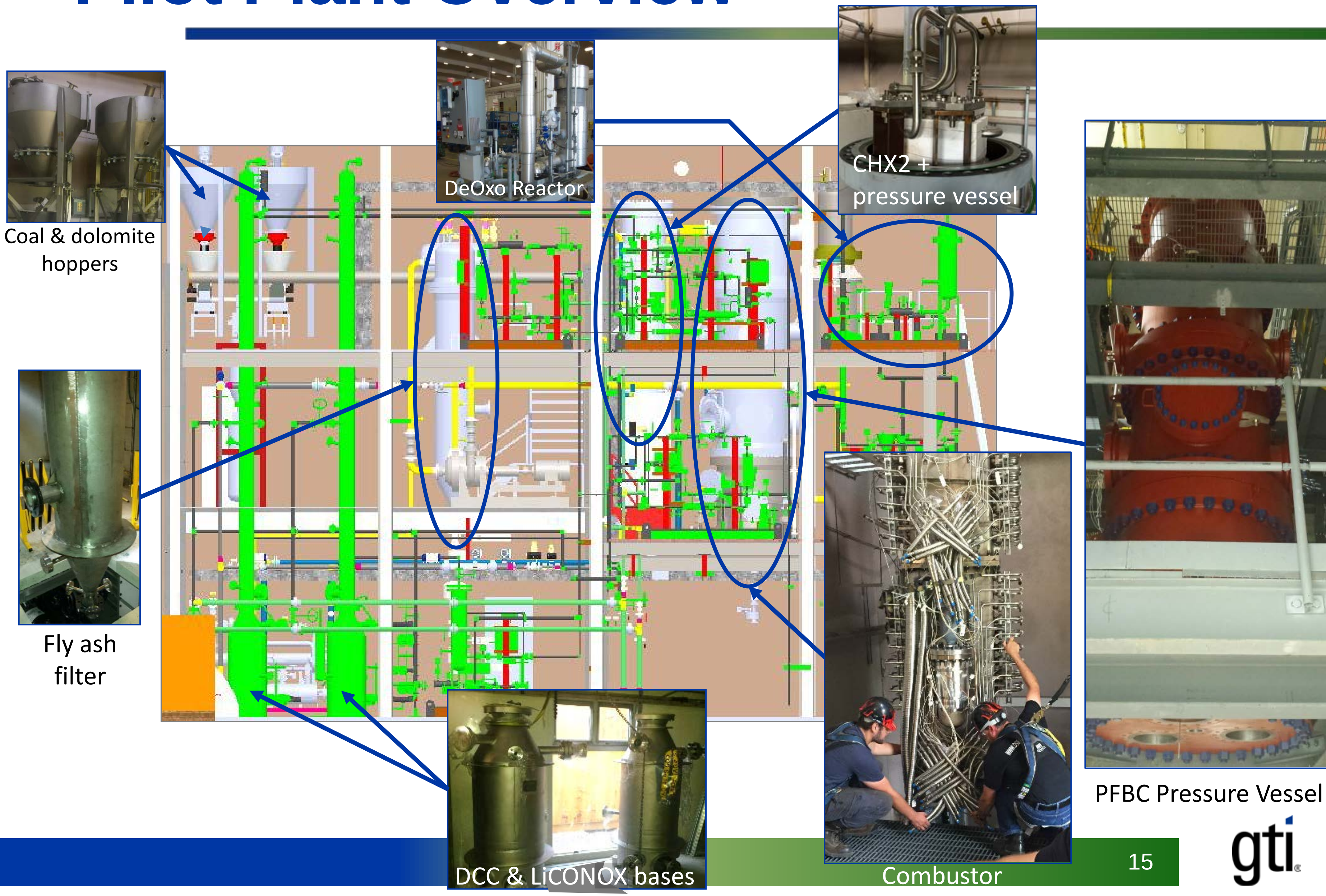
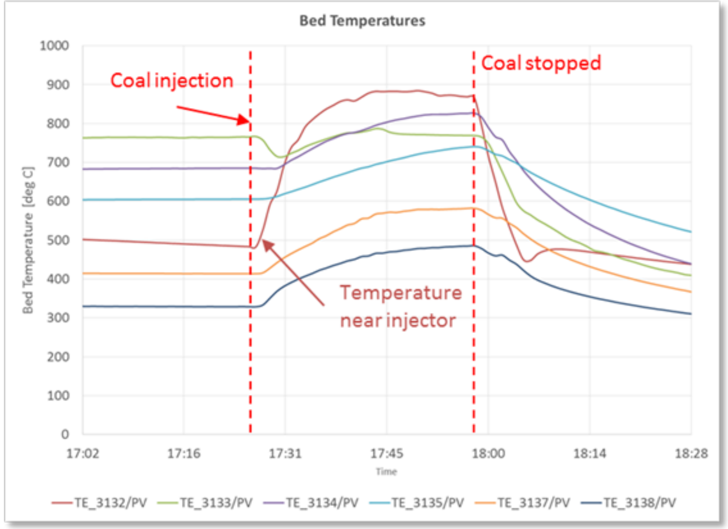
Significant Accomplishments

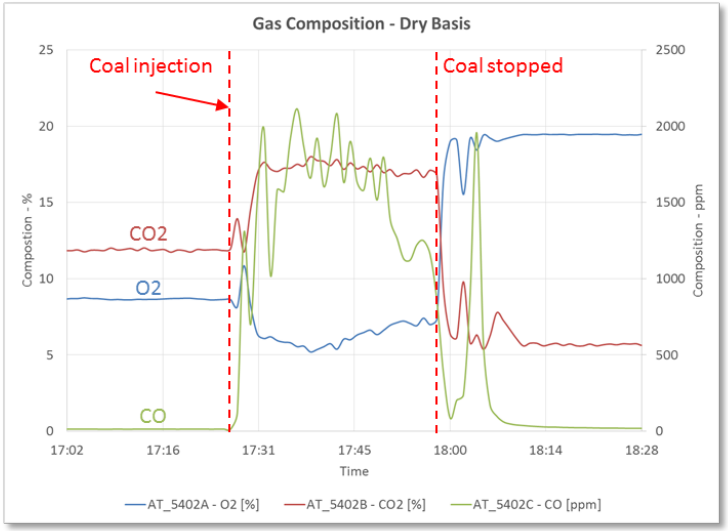
- 1 MWth pilot plant construction completed at CanmetENERGY
- Commissioning tests demonstrated:
  - Coal ignition and burning in combustor
  - CO_2 Purification Unit operation
    - Direct contact cooler operation with combustor flue gas
    - Liconox and DeOxo in standalone tests
- Initial performance testing also demonstrated:
  - Air and oxy-combustion ignition / operation
  - Pure oxy-combustion operation at full pressure (120 psia)
  - Validated sulfur capture method in bed with 95-99% capture

Pilot Plant Overview



Oxy-PFBC Commissioning Results





- Plant was successfully commissioned, including component and system testing
- Successful ignition and sustained burning demonstrated
  - Ignition was robust and repeatable as parameters varied
  - Varied bed mass and mass flow for: coal, natural gas, oxidizer, recycle gas

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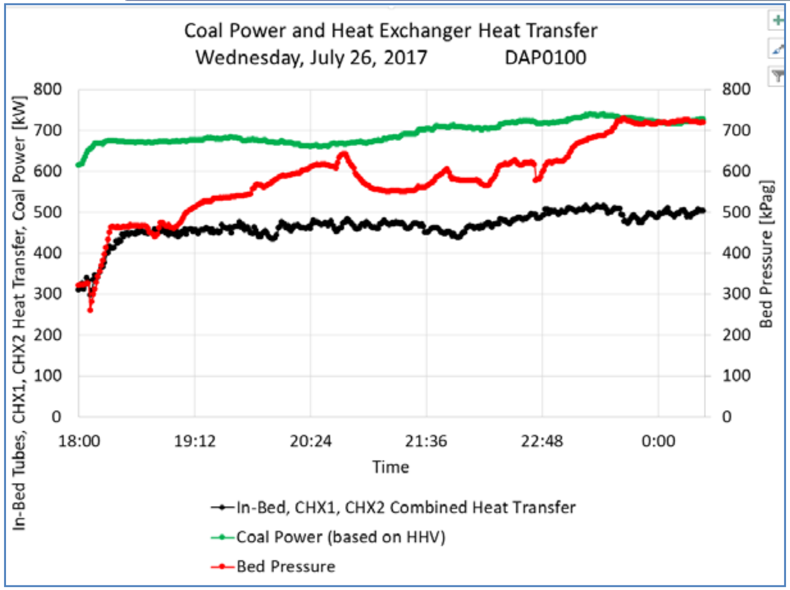
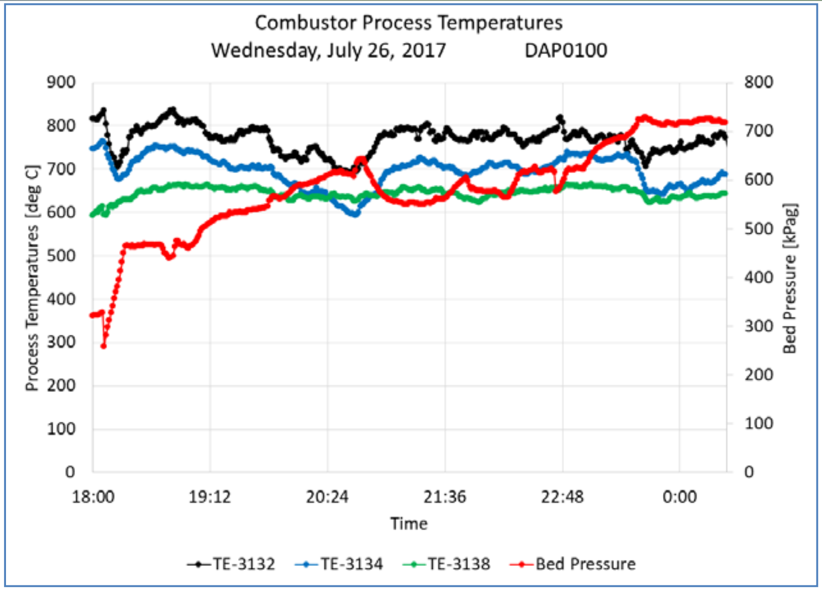
Oxy-PFBC Test Results





- Initial testing demonstrated successful oxy-combustion at full operating pressure
  - Demonstrated ignition and burning in both oxy-fired and air-fired modes
  - Ignition at 300 kPag, then ramped up to over 700 kPag
  - Temperature variation in bed of ~125-175 ^{o}C
  - Fuel feed at ~0.7 MWth

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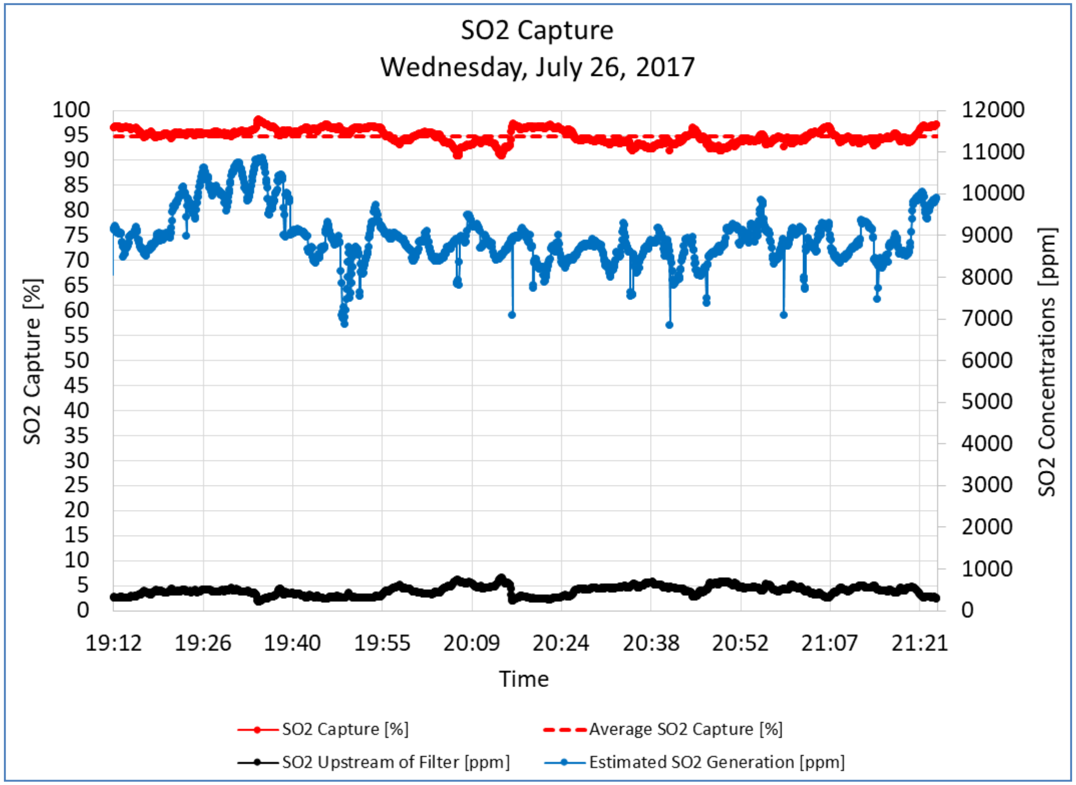
Oxy-PFBC Test Results



- Demonstrated average sulfur capture of 95% in the fluidized bed
- Sulfur capture downstream of filter estimated at >99% prior to entering CO_2 purification unit

CO_2 Purification Unit Test Results

Parameter or Relationship	How achieved	Implications of Test
DCC Temp & Condensate Flow control	Test performed with heated air and flue gas of natural gas combusted with air	Systems working
DCC Level & Temp Trips	Test performed with water	Systems working
LICONOX® Temp & Condensate Flow control	Test performed with heated air	Systems working
LICONOX® Level, Condensate Flow and Acidity (pH) control	Test performed with water and caustic solution	Systems working
DeOxo start up heater & HEX	Test performed with air and CO_2	Systems working
DeOxo O_2 conversion, along with Temp and Composition (HC & O_2) trips	Test performed with synthetic flue gas	Systems working

- CPU successfully commissioned and ready for performance testing with flue gas from oxy-coal PFBC
- Limited DCC tests so far performed with low pressure flue gas from air fired natural gas ($P<1.5$ Bara, H_2O conc. < 10%) confirmed efficient water condensation under controlled conditions

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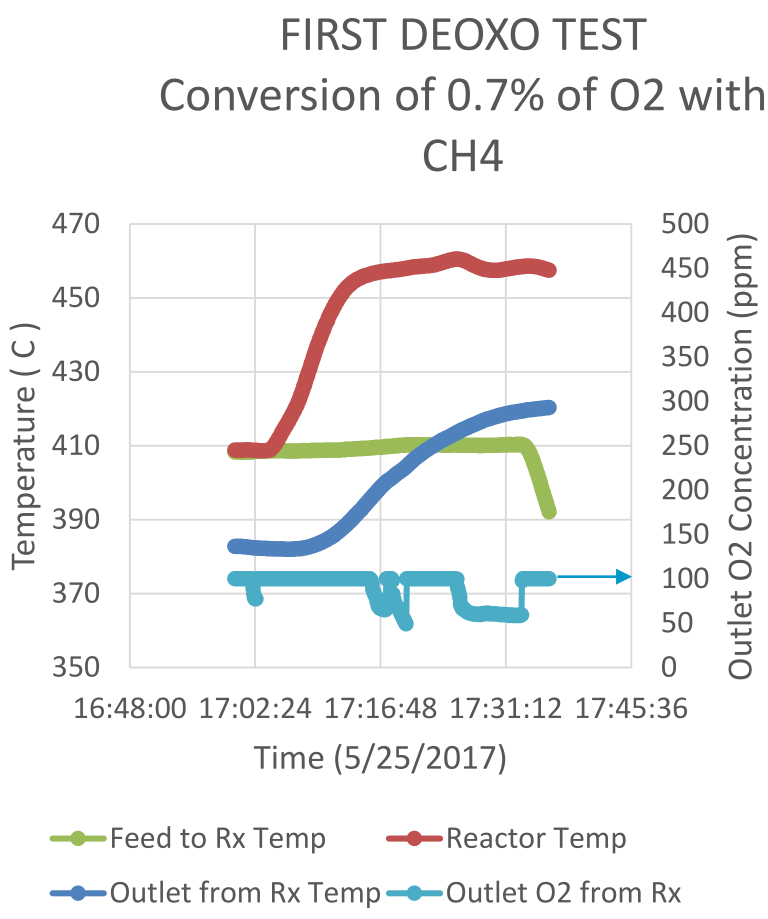
CO_2 Purification Unit Test Results



- Encouraging initial DEOXO test
  - Achieved performance targets using synthetic flue gas
  - O_2 Conversion > 99%
  - CH_4 Slip < 0.1 %
- Operating conditions
  - Feed to DEOXO Reactor: 0.7% O_2, 2.6% N_2, 0.4% CH_4, 96.3% CO_2
  - P=6 Bara
  - Inlet T=410 C
- Future testing planned with Oxy-PFBC flue gas

Oxy-PFBC Lessons Learned

- Promising initial results with no significant issues or showstoppers identified
- Early tests provided significant learning on how to start and control the system
- Initial tests had more bed expansion than anticipated – bed particles too small
  - Bed covered more active heat exchanger tubes than expected
  - Result was overcooling of the bed and poor carbon conversion
- Test ended prematurely due to erosion of coal feed line
  - Erosion due to tight radius bends and excessive velocity
- Issues being corrected with next test scheduled for mid-September

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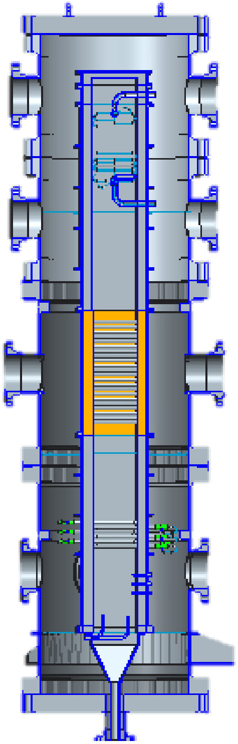
Future Plans

- Phase II plans
  - Complete pilot scale testing
    - Update performance and technoeconomic analysis
    - Material and TRL evaluation
    - Anchor analysis codes
  - Complete commercialization activities



1 MWth pilot scale Oxy-PFBC

Oxy- PFBC Commercialization Plan

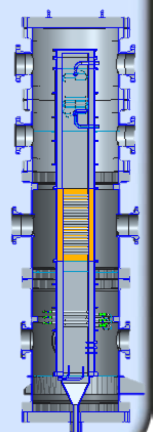
Phase I – 2012 – 2013	Phase II – 2014 – 2017	Phase III – 2018 – 2022	Phase IV – 2021 – 2026

Cold Flow Testing & Bench Scale Kinetics (TRL 3)

Demonstrates:
- Coal & sulfation reaction rates at high CO_2 and H_2O partial pressure
- Heat transfer coefficients
- Bubble control
- Residence time

Pilot Plant (TRL 6)

Demonstrates:
- Pressurized system operation
- Elutriated bed operation and chemistry
- Flue gas clean-up
- Erosion risks



Duty ~1 MWth
Size ~1 foot scale

Large Pilot / Demo Plant

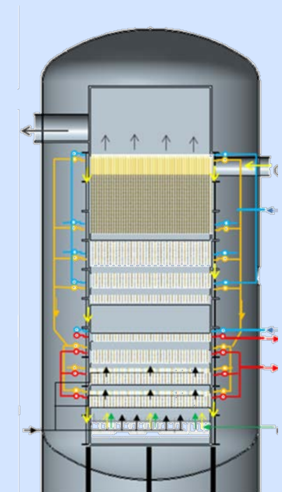
Demonstrates:
- Operation at scale
- Component life
- Operating parameters
- Maintenance approaches
- Erosion risks

~30-50 MWth
~3-4 foot scale

Commercial Demonstration

5+ years

Validates:
- System efficiency
- Capital costs
- O&M costs



275+ MWe
~20+ foot scale

Plan for commercial scale demonstration by 2026

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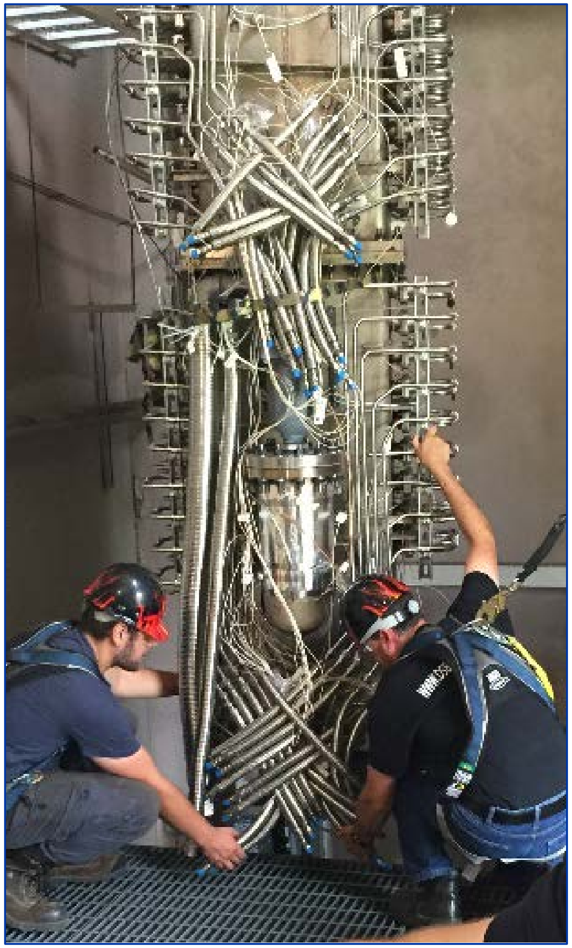
Summary

- Commissioning and initial tests completed
  - Combustor demonstrated robust ignition, oxy-combustion at full pressure
  - Demonstrated excellent in-bed sulfur capture
  - DeOxo achieved performance goals with synthetic flue gas
- TEA update
  - Exceeds DOE goals, with >50% reduction in CO_2 capture penalty relative to DOE Case 12
- Next test planned for September



Lowering combustor into pressure vessel at CanmetENERGY

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NETL Program Manager: Robin Ames

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